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Super-Fluids and Quantum-Fluids – A Brief Review

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Abstract
This particular paper gives a brief account of quantum fluids and Super-fluids, their intrinsic connection, the insights they provide regarding completely new structures and the way matter behaves at relatively much lower temperatures. Super-fluids and quantum fluids are compared taking the example of liquid Helium-2 and its isotopes Helium-3 and Helium-4 (Superfluid). The typical behavior of Helium at very low temperatures mainly highlights the viscosity parameter which turns down to zero for a free flow of helium through the holes a little larger than atomic sizes. The same viscosity is much larger for quantum fluids as only a fraction of electrons or protons behave as fluid. Moreover, solid Helium-4 under high pressure behaves as if some part of it was a super-fluid. This indicates that quantum fluids and super-fluids indeed have a distinction in their behavior with respect to temperature and pressure. This means that viscosity is going down when the quantum fluid is having its transition to a super-fluid. This will be dealt a little later. Quantum vortices in super-fluids are also discussed briefly.

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1. Introduction

Quantum fluids and Super-fluids share certain similarities, but its the pressure range which makes the super-fluid to remain in the liquid state approximately down to absolute zero which is evident in case of helium-3 and Helium-4, but in case of quantum fluids, there is only a certain fraction of its electrons or protons which behave like a fluid.

2. Quantum Fluids

Any system that generally exhibits quantum mechanical effects at the macroscopic level such as super-fluids, superconductors, ultra-cold atoms, etc is known as a quantum fluid. Most of the matter can either be solid or gaseous (at low densities) near absolute zero. But, for the cases of helium-4 and its isotope helium-3, we find a pressure range where they can remain liquid down to absolute zero temperature, mostly because the amplitude of the quantum fluctuations experienced by the helium atoms is larger than the inter-atomic distances. In the case of solid quantum fluids, it is only a fraction of its electrons or protons that behave like a "fluid". One prominent example is that of superconductivity where quasi-particles made up of pairs of electrons and a phonon act as bosons which are then capable of collapsing into the ground state to establish a super-current with a resistivity nearly zero.

Figure 1: The (Shy) Bosons occupying the same state and the (Royal) Fermions occupying the separate energy states. Note that there is a Fermi level.

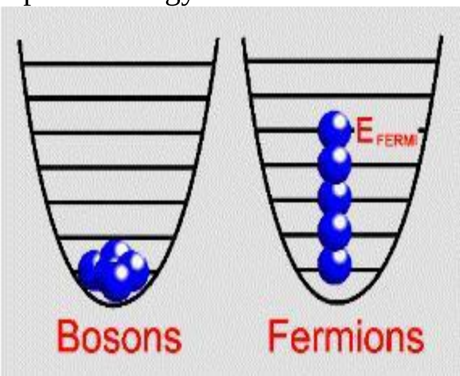


Figure 2: The lowest temperatures reached for bulk matter between 1970- 2000 AD.

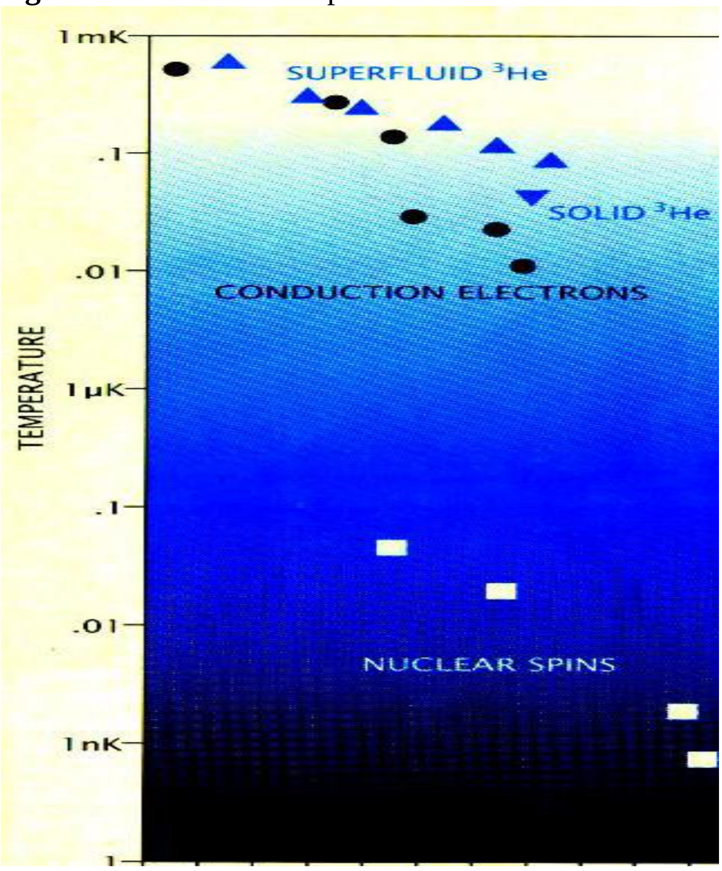


Figure 3: The Fountain effect - Also known as the thermo-mechanical effect. When radiation warms a super-fluid, the expansion pushes up the free surface of the liquid forming a fountain. This causes liquid helium II to flow up the sides of open containers.

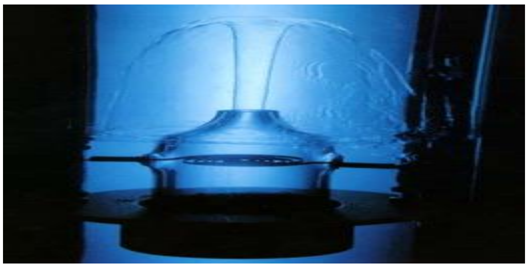


Figure 4: Different vortex patterns in super-fluid He-3

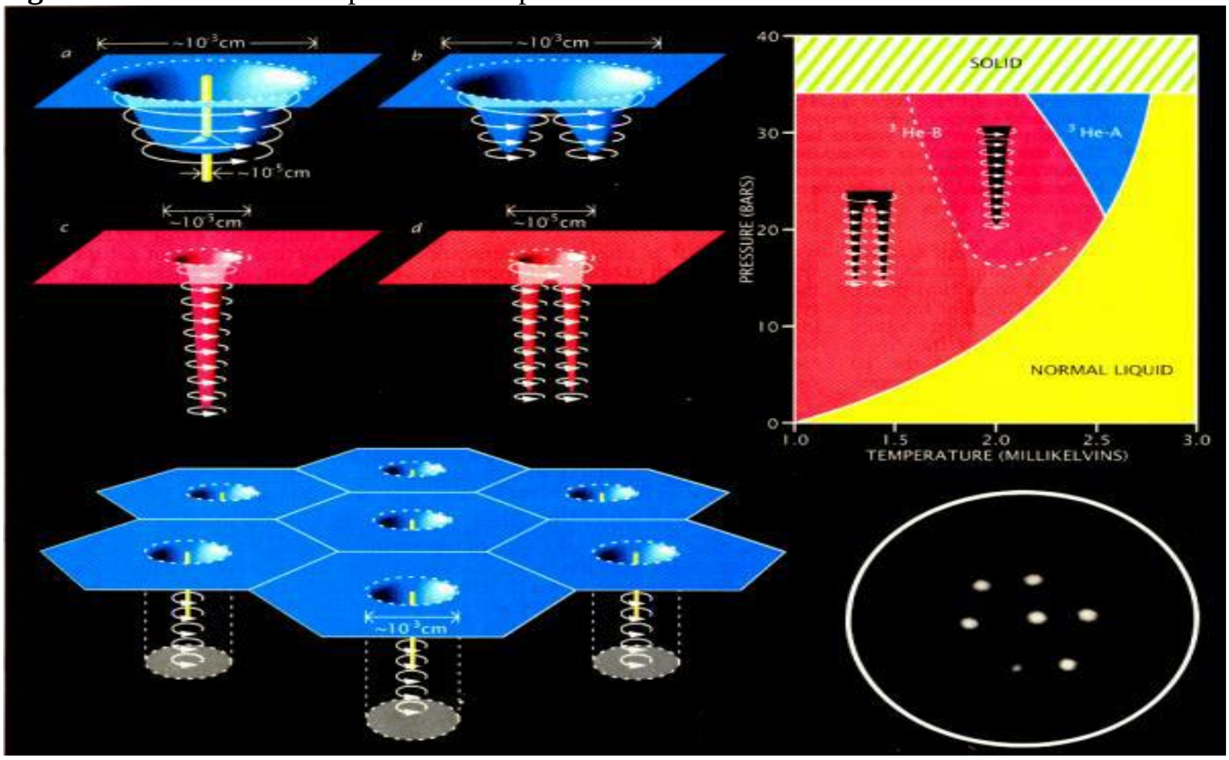
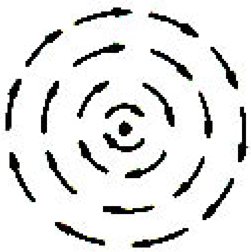


Figure 5: super-fluid moving around vortex core



3. Superconductivity and Super-fluidity – an interesting comparison

Superconductivity was found in 1911 by Kammerlingh Onnes in Leiden, in Al at 1.3K.Superfluidity in 4 He at 2.2K was not discovered until 1938, by Allen & Meissner in Cambridge, & Kapitza in Moscow (who performed tedious investigations of its properties). Indications were available between the intrinsic connection between Superconductivity and Super-fluidity at that time, but the discoveries took their own course of time, Superconductivity being the first and then Super-fluidity followed.

Figure 6: Phase Diagram of He-4

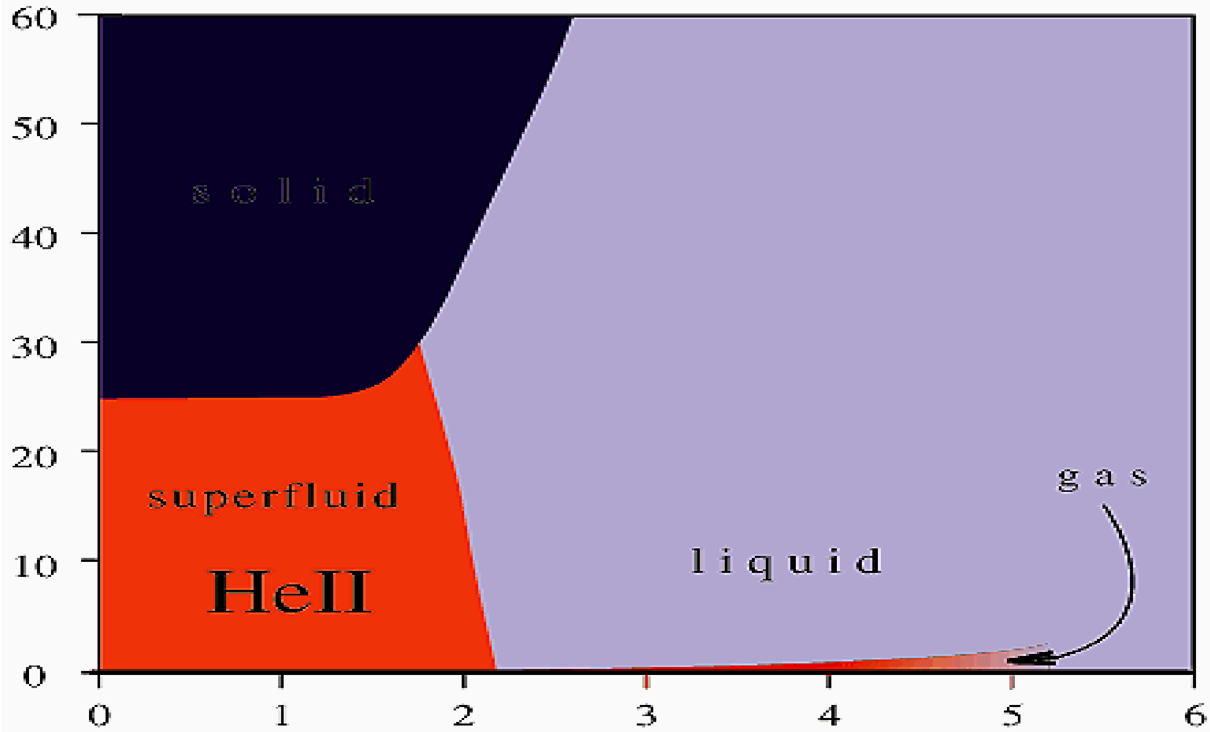
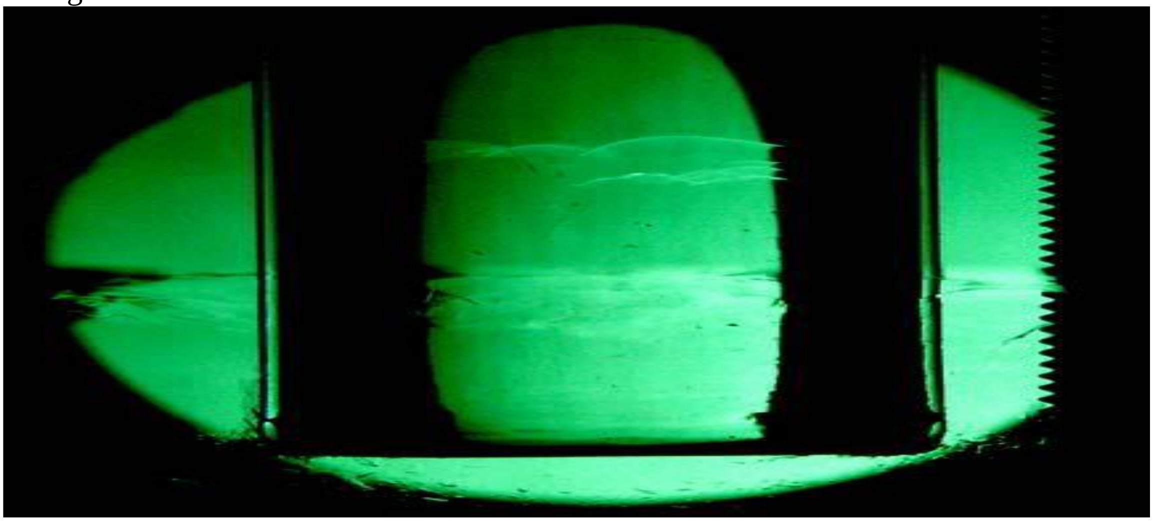


Figure 7: Photo (taken from video) of the liquid & solid phases, with fluid flowing through the solid



Both of these phenomena are found to have high co-relation following the serious investigations of Meissner and kapitza. Theoretical understanding only came gradually, & required several key ideas- Bose-Einstein (1894-1984) condensation (BEC), the macroscopic wave- function, and fermion pairing to give fermionic BEC. As experiments went to even lower temperatures, more & more systems were seen to go super-fluid/superconducting – a major triumph was the long- awaited discovery of superfluid 3 He at 2.7 mK (Osheroff et al.,) recently.

4. Reaching down to Absolute Zero

Now, what is the means by which we land at such low temperatures? We have seen the voyages to inner & outer space in physics. There is also a voyage to the ultra-cold.

One can never reach absolute zero (where all random thermal motion stops), since no

cooling device is perfectly reversible- which means something always leaks back. The fascination of ultra-low T is that more & more complex kinds of 'quantum order' develop, practically undisturbed by the thermal motion. This has led to some of the most extraordinary phenomena in physics. The experimental techniques which get to such temperatures are equally remarkable. Cooling is done in stages– one first cools by pumping on gases to liquify them. This mostly works down to 0.3K, after which one mixes super-fluids & polarizes spins with strong fields. We can then remove the fields – the spins then 'suck up' the thermal energy to randomize their directions. In the terminology of physics, **cryogenics** is the study of the production and behavior of materials at very low temperatures. The below figure shows the various temperature ranges at which Helium behaves as solid and super-fluid.

5. Condensed matter and Super-fluidity

Super-fluidity is seen, in the absence of viscous resistance to the flow of a fluid. The super-fluid flows freely, ad infinitum, through holes hardly larger than atomic size. The 'fountain effect' below shows free flow of He-4 liquid. The ultimate explanation of this is in the Bose statistics of the particles. He-4 atoms are bosons (with 2 electrons, 2 protons, & 2 neutrons). At low T they all 'Bose condense' into the same quantum state. The super-fluidity then arises because it takes a finite energy to excite the system out of this state- only possible if it flows faster than a 'critical velocity' Vc , or if some object moves through it faster than Vc .The Critical velocity plays a major role in super-fluids. Super-fluidity was originally discovered in liquid helium, by Pyotr Kapitza and John F Allen (Kapitza.p., 1938; Allen.J.F AND Misener. A.D., 1938). It has since been described through phenomenology and microscopic theories. In liquid helium-4, the super-fluidity occurs at far higher temperatures than it does in helium-3. Each atom of helium-4 is a boson particle, by virtue of its integral spin. On the contrary, a helium-3 atom is a fermion particle; it can form bosons only by pairing with itself at much lower temperatures. This process can be viewed similar to the electron pairing in superconductivity.

The fountain effect in helium is found to be a very interesting phenomena and its also termed as a thermo-mechanical effect as its driven by the heat energy given by the radiation and when it tries to warm up the super-fluid, the expansion will push up the free surface of the liquid resulting in a beautiful fountain pattern. This even causes the liquid helium-2 to flow up the sides of open vessels.

6. Discussion and a Brief Theoretical Analysis

6.1 Macroscopic wave-functions

If all the particles Bose condense in the same state, we can conveniently write a 'macroscopic wave-function' for the quantum state of the entire system. This was first noticed by London in 1937-38, that this was the key to super-fluidity & superconductivity. Lev D. Landau gave a phenomenological theory in 1941 for super-fluid 4 He, & then finally in 1957 the BCS (Bardeen-Cooper-Schrieffer) theory, & an equivalent theory of Bogoliubov, gave a definitive explanation of superconductivity (where fermionic electrons 'pair' to form bosons which then go super-fluid). The generalization to super-fluids with rotating pairs with spin was given by Leggett & others. The BCS macroscopic quantum state for a set of bosons is written in the form Ψ (r 1, r 2, .r N) = Σ perm φ (r 1) φ (r 2) ...φ (r N) where the sum is over all possible swaps of the particles (remember the particles are indistinguishable). This formula may look terrible, but it just says that all particles are in the same quantum state φ . All particles are in the same state, and hence we can talk about a single quantum state Ψ (r) for the entire super-fluid. This is known as London's famous 'macroscopic wave-function'. It is still aprobability amplitude! London's idea was initially disbelieved when, but is now a

central part of physics. Thus we see a new kind of ‘quantum emergence’ beginning to appear – not yet based on macroscopic entanglement, but on Bose condensation. Nevertheless it has spectacular macroscopic effects too. Moreover, disbelief of a radical idea is common in science. But, later, the same radical idea takes a strategic U-turn to strike and trigger important discoveries too.

6.2. Quantum Vortices in Super-fluids

Suppose we look at a vortex in a superfluid- ie., fluid circulating around a core. From what we saw with atoms this tells us we have probability waves circulating round the core with wavelength $\lambda = h/p = h/mv$, where v is the velocity of the atoms circulating round the core. But then, as noted by Onsager in 1950, as in atoms, only certain velocities are allowed, if we are to fit the waves around the core. Hence we find that the total circulation is quantized- we have ‘quantized vortices’. In this simple picture the core is like a string- in fact it has a finite diameter. In He-4 this is indeed very small (only about 1 Angstrom!), but in other super-fluids like He-3 it is much larger (~150 Angstroms), & so the core is itself very complex.

In most cases quantum vortices are a type of topological defect exhibited in super-fluids and superconductors. In a super-fluid, a quantum vortex "carries" quantized orbital angular momentum, thus allowing the superfluid to rotate; in a superconductor, the vortex carries quantized magnetic flux. Now in physics, a quantum vortex represents a quantized flux circulation of some physical quantity. The existence of quantum vortices was proposed by Lars Onsager in 1947 in connection with superfluid helium. Onsager also pointed out that quantum vortices describe the circulation of superfluid and conjectured that their excitations are responsible for superfluid phase transitions.

7. Super-solids

In 2004 a remarkable discovery was made by a group solid under M Chan. It was found that a sample of solid He-4, under very high pressures, behaved as if some fraction of it was super-fluid. In other words, even though the system remained rigid, and the crystalline order in it was maintained, nevertheless some part of it could ‘super-flow’,ie., flow without resistance. This remarkable behavior has been seen in several ways. The original discovery rotated the solid in a sealed ‘bucket’-shaped container –part of the contents did not rotate but stayed stationary in the lab frame. In a second experiment, super-fluid He flowed through the solid- which was even filmed on video.

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Conclusion

Quantum fluids and Super-fluids had been compared briefly in this paper. The various parameters that mainly distinguish quantum fluids and super-fluids are the pressure,

temperature and viscosity. Of course, numerous experiments provide much more parameters, but the main parameters are those that are listed above that definitely make an impact.

Limitations and Further Scope

This paper does compare the quantum fluids and super-fluids briefly. Moreover, the mathematical equation of state describing the exact transition of the quantum fluid to super-fluid state of Helium needs to be worked out involving the quantum wave-functions and mathematical functions intrinsically involving viscosity. This correlation can turn out to be a very important factor in this regard. Moreover, viscosity needs to be studied from a deep quantum mechanical viewpoint as it forms a major parameter that actually defines a super-fluid. In this regard, the fluid equations involving Navier-stoke's equations and some approximate solutions can try to come to our rescue, which is still a radical idea. If the equation of state invokes viscosity from a quantum mechanical viewpoint, then the parameters like critical velocity, lambda point etc can be further understood. Till now, mostly we do not have a quantum mechanical Navier-stoke's equation. Since, the viscosity itself goes down to practically zero forcing the quantum mechanical effects to take over; hence it needs to be understood better.

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